

The Parkes Pulsar Timing Array Project

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Abstract. Detection and study of gravitational waves from astrophysical sources is a major goal of current astrophysics. Ground-based laser-interferometer systems such as LIGO and VIRGO are sensitive to gravitational waves with frequencies of order 100 Hz, whereas space-based systems such as LISA are sensitive in the millihertz regime. Precise timing observations of a sample of millisecond pulsars widely distributed on the sky have the potential to detect gravitational waves at nanohertz frequencies. Potential sources of such waves include binary super-massive black holes in the cores of galaxies, relic radiation from the inflationary era and oscillations of cosmic strings. The Parkes Pulsar Timing Array (PPTA) is an implementation of such a system in which 20 millisecond pulsars have been observed using the Parkes radio telescope at three frequencies at intervals of two – three weeks for more than two years. Analysis of these data has been used to limit the gravitational wave background in our Galaxy and to constrain some models for its generation. The data have also been used to investigate fluctuations in the interstellar and Solar-wind electron density and have the potential to investigate the stability of terrestrial time standards and the accuracy of solar-system ephemerides.

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INTRODUCTION

The existence of gravitational radiation is a key prediction of relativistic theories of gravity. These waves propagate at the speed of light and are generated by the acceleration of massive bodies. Astrophysical sources of gravitational waves (GW) include relic radiation from the inflation era [1, 2], radiation from reconnection and oscillations of cosmic strings [3], supernovae and formation of compact stars and black holes [4], binary super-massive black holes in the cores of galaxies [5, 6, 7], coalescence of double-neutron-star binary systems [8] and short-period X-ray binaries in our Galaxy [9]. Some of these sources may be individually detectable, others combine to form an essentially isotropic and stochastic background of GW which permeates all of space.

Observations of orbital decay of double-neutron-star binary systems have provided irrefutable evidence that gravitational radiation exists and that its power is accurately described by Einstein’s general theory of relativity [10, 11]. However the signal expected at the Earth from any realistic source is exceedingly weak, with typical strain amplitudes of order 10^{-22} at frequencies of order 1 Hz. Despite considerable efforts over more than 40 years, up to now there has been no confirmed direct detection of GW. Initial efforts used the massive bar detectors pioneered by Joseph Weber [12] but more recent detectors with higher sensitivity are based on laser interferometer systems, for example, the ground-based systems LIGO [13] and VIRGO [14] and the proposed space interferometer LISA [15]. The ground-based interferometers are sensitive to GW with frequencies in the range

10 – 500 Hz, whereas LISA is sensitive to frequencies in the range 0.1 – 100 mHz. Initial LIGO is now operating and has set limits on various sources [e.g., 16]; higher sensitivity will be achieved with Advanced LIGO which is due for completion in 2011. The launch date for LISA is rather uncertain but is unlikely to be before 2017.

Pulsars, especially millisecond pulsars (MSPs) are incredibly precise clocks making possible many interesting applications. Of most interest to us here is the use of MSPs as GW detectors. GW passing over pulsars and over the Earth will modulate the received pulsar period; the net effect is the difference in the modulation at the two ends of the path [17]. Pulsar timing experiments measure variations of pulse phase relative to model predictions. They are therefore most sensitive to long-period GW with periods comparable to the data span, typically several years, which corresponds to frequencies in the nanoHertz regime. Even for these long periods, the expected timing residuals are very small. Simulations using TEMPO2 [18, 19] show that a binary system consisting of two $10^9 M_{\odot}$ black holes with a 4-yr orbital period in a galaxy at redshift 0.5 will produce a timing residual of amplitude just 1.5 ns. Although such a signal would be very difficult to detect with current technology, expected levels of the stochastic GW background from binary super-massive black holes in galaxies are considerably higher with millions of galaxies throughout the Universe contributing. Predicted levels of the GW background from other sources such as the inflation era and cosmic strings, while much more uncertain, are at comparable levels and are potentially detectable.

Other sources of “noise” exist in pulsar timing data

and if we wish to detect GW using pulsar timing we have to be able to separate these different effects. With timing observations of just one or even a few pulsars, upper limits may be set but a positive detection is not possible. However, a large sample of pulsars widely distributed on the sky — a pulsar timing array — can in principle *detect* GW with frequencies in the nanoHertz range.

PULSAR TIMING ARRAYS

A pulsar timing array consists of a number of pulsars which are widely distributed on the sky and are observed at (quasi-)regular intervals over a long time. Typical data spans are many years and typical observation intervals are a few weeks. To allow correction for interstellar and Solar-system propagation effects, observations at several frequencies are required. Such an array has the potential to make a direct detection of GW with frequencies in the nanoHertz range. It also can define a “pulsar timescale”, which may be more stable over long time intervals than timescales based on atomic frequency standards, and to detect errors or omissions in the models of Solar-system dynamics used to define the Solar-system barycentre. For example, timing arrays have the potential to refine mass estimates for the outer planets and to detect previously unknown trans-Neptunian objects. The concept of a pulsar timing array was first introduced by Hellings and Downs [20] and was further developed (and the name coined) by Romani [21] and Foster and Backer [22].

The key point which enables a pulsar timing array to separate the effects of a GW from other contributions to observed timing irregularities is that the signals from the different sources have different spatial correlation signatures. In other words, the correlations between timing residuals for pulsars in different directions on the sky are different for the various noise sources. GW have quadrupolar symmetry and so pulsars separated on the sky by 90° are modulated in opposite senses, whereas those separated by 180° have the same sense of modulation. For an isotropic background, the effect is independent of the orientation of the angle between the two pulsars. A simulation of the effects of a stochastic and isotropic GW signal on correlations between timing residuals and the predicted correlation [20] are shown in Fig. 1.

Although MSP periods are very stable, they are not perfectly so. Intrinsic timing noise tends to have a red spectrum [23], similar to that of the expected GW background. However, timing noise in different pulsars is uncorrelated between the pulsars and so will just add extra noise to the expected GW signature. Other sources of noise include clock errors and errors in the planetary ephemeris used to correct observed pulse arrival times (ToAs) to the Solar-system barycentre. Both of these are

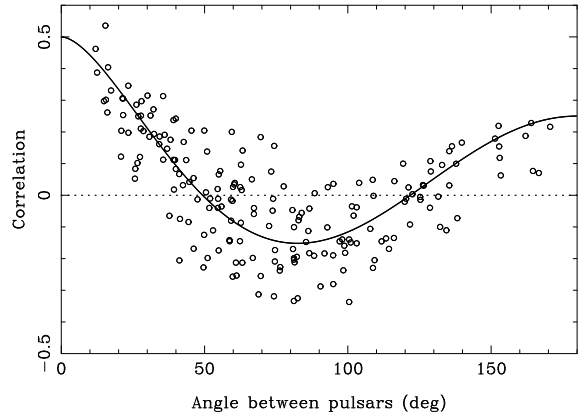


FIGURE 1. Pairwise correlations between simulated timing residuals for 20 pulsars as a function of angle between the pulsar pairs. The timing residuals are dominated by the effects of an isotropic stochastic GW background — there is no intrinsic pulsar period noise — and the scatter of the points around the expected correlation results from the stochastic nature of the GW signal. [19]

correlated in different pulsars, but they have different spatial signatures and therefore can be separated. Clock errors will produce the same residuals for all pulsars and hence will have a spatial monopole signature. Ephemeris errors are equivalent to an error in the Earth velocity and hence have a dipole signature on the sky. A constant error or linear change in clock rate and constant offsets in the Earth’s velocity or acceleration will all be absorbed into the fitted pulsar periods and period derivatives, but higher order changes in these quantities are in principle detectable. Likewise, signals from GW with periods longer than the data span will be absorbed by the pulsar period fitting.

THE PARKES PULSAR TIMING ARRAY

The Parkes Pulsar Timing Array (PPTA) project is using the Parkes 64-m radio telescope to time 20 MSPs at intervals of two to three weeks. Observations commenced in early 2005 and are made at three frequencies, 685 MHz (50cm), 1400 MHz (20cm) and 3100 MHz (10cm) with bandwidths of 64 MHz, 256 MHz and 1024 MHz respectively. The project is a collaborative effort with principal partners at the Swinburne University of Technology, the University of Texas at Brownsville and the ATNF. Fig. 2 shows the sky distribution of MSPs which are suitable for pulsar timing array experiments and those chosen for the PPTA.

Observations at 1400 MHz normally use the central beam of the Parkes 20cm multibeam receiver [24] which has a system equivalent flux density of about 30 Jy. A dual-frequency coaxial 10cm/50cm receiver [25] allows

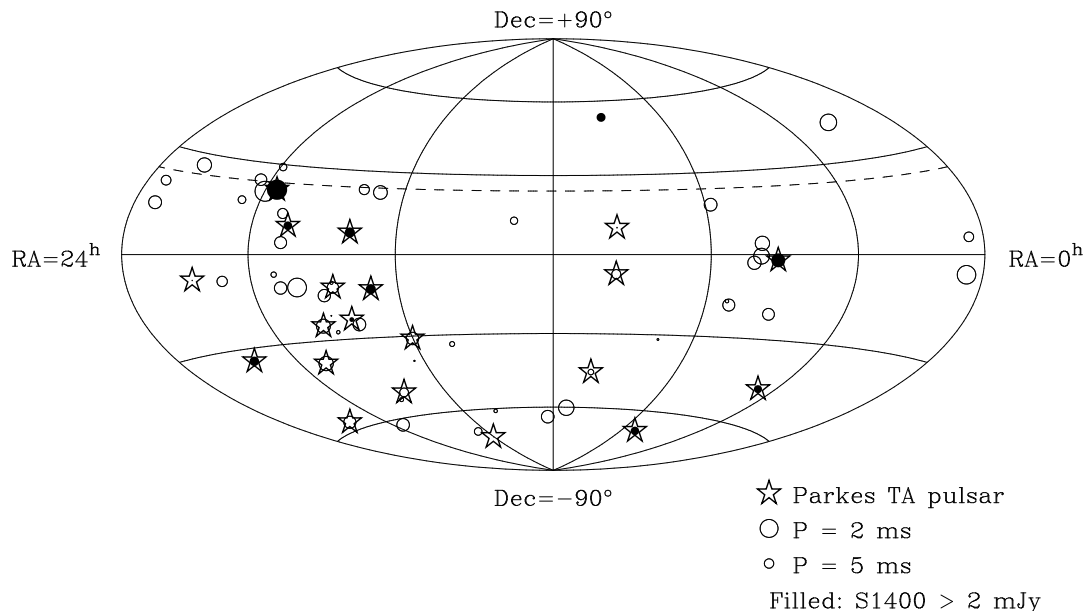


FIGURE 2. Distribution in celestial coordinates of known Galactic disk MSPs (with one exception, PSR B1821–24 in the globular cluster M28) which are suitable for pulsar timing arrays. The size of the circle is inversely related to the pulsar period and for stronger pulsars the circle is filled. The dashed line is the northern declination limit of the Parkes radio telescope. Pulsars being timed as part of the PPTA project are marked with stars.

simultaneous observations at 3100 and 685 MHz; the system equivalent flux densities of these receivers are approximately 48 Jy and 64 Jy respectively. All receivers receive orthogonal linear polarisations and have provision for injection of a linearly polarised calibration signal at 45° to the two signal probes. Two main backend systems are used: a digital filterbank (DFB) and CPSR2, a baseband system allowing coherent dedispersion of two dual-polarisation 64 MHz bands [26]. The DFB system (PDFB1) has a maximum bandwidth of 256 MHz and provides on-line correlation and folding at the topocentric pulsar period giving pulse profiles in all four Stokes parameters. DFB data files are written using the PSRFITS format and all processing uses the PSRCHIVE data analysis system [27] and the TEMPO2 timing analysis system [18, 28, 19].¹

Table 1 lists the pulsars being observed and gives the current rms timing residual based on one-hour observations and a two-year data span. Obvious interference has been excised from the observations, but they are neither corrected for DM variations nor accurately calibrated. Only one frequency derivative has been fitted, apart from PSR J1939+2134 (PSR B1937+21) where three derivatives are fitted.

The sensitivity of the PPTA to a stochastic background

of GW was investigated by Jenet et al. [29]. They showed that weekly observations of the 20 MSPs with rms timing residuals of order 100 ns over a five-year data span was required to detect the predicted GW background from binary super-massive black holes in galaxies. It is clear that our current observations do not reach this goal.

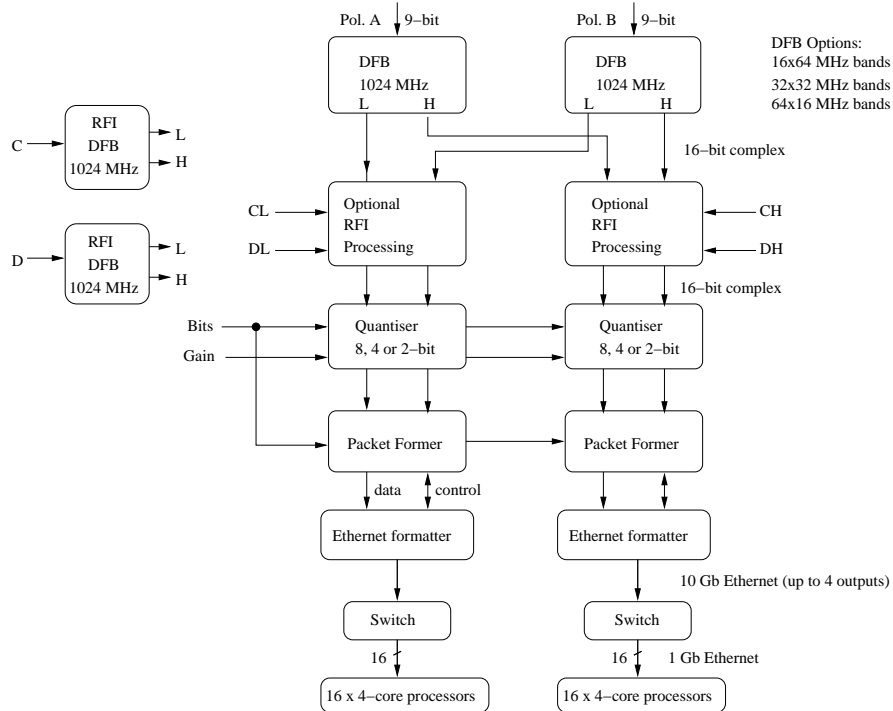
Several different avenues to improving our data quality are being explored. Firstly we are developing new backend systems which will have better sensitivity and higher time and frequency resolution. A new DFB system with 1024 MHz bandwidth (PDFB2) was commissioned in 2007 May. First observations with this do have improved performance, but are still limited for the stronger pulsars by systematic effects which are not currently fully understood. This system will be further developed later this year (PDFB3) to double the processing power, provide real-time mitigation of interference using an adaptive filter algorithm [30], write streamed multi-frequency data to disk for search-mode observations and provide baseband signals over a maximum bandwidth of 1024 MHz for the next-generation baseband system (APSR) which is being developed by the Swinburne University group in conjunction with the ATNF. Fig. 3 shows a block diagram of the PDFB3/APSR system.

Secondly, we are continually improving our data analysis systems, PSRCHIVE and TEMPO2. New methods of displaying, manipulating and calibrating the data are being developed. As an example, we recently investigated the effect of DM variations on our data [31]. Fig. 4 shows

¹ See also <http://psrchive.sourceforge.net> and <http://www.atnf.csiro.au/research/pulsar/tempo2>

TABLE 1. PPTA pulsars and their RMS timing residuals

PSRJ	Pulse Period (ms)	DM ($\text{cm}^{-3} \text{ pc}$)	Orbital Period (d)	RMS Residual (μs)
J0437-4715	5.757	2.65	5.74	0.12
J0613-0200	3.062	38.78	1.20	0.83
J0711-6830	5.491	18.41	—	1.56
J1022+1001	16.453	10.25	7.81	1.11
J1024-0719	5.162	6.49	—	1.20
J1045-4509	7.474	58.15	4.08	1.44
J1600-3053	3.598	52.19	14.34	0.35
J1603-7202	14.842	38.05	6.31	1.34
J1643-1224	4.622	62.41	147.02	2.10
J1713+0747	4.570	15.99	67.83	0.19
J1730-2304	8.123	9.61	—	1.82
J1732-5049	5.313	56.84	5.26	2.40
J1744-1134	4.075	3.14	—	0.65
J1824-2452	3.054	119.86	—	0.88
J1857+0943	5.362	13.31	12.33	2.09
J1909-3744	2.947	10.39	1.53	0.22
J1939+2134	1.558	71.04	—	0.17
J2124-3358	4.931	4.62	—	2.00
J2129-5721	3.726	31.85	6.63	0.91
J2145-0750	16.052	9.00	6.84	1.44

**FIGURE 3.** Block diagram of the PDFB3/APSR system currently under development by the ATNF and Swinburne University. The C and D inputs may be used for real-time interference mitigation system (as drawn) or may be used for an independent DFB system. Input signals are Nyquist sampled with 9-bit precision.

observed variations in DM for the 20 pulsars of the PPTA sample. Significant long-term variations are observed for most of the sample with typical changes of a few times $10^{-3} \text{ cm}^{-3} \text{ pc}$ over the two years. If not taken into account, these variations will introduce noise into the measured ToAs making the task of detecting GW, clock errors and ephemeris errors more difficult.

LIMITS ON THE GRAVITATIONAL-WAVE BACKGROUND

Although we do not yet have sufficient sensitivity to detect the expected stochastic GW background we can put limits on its amplitude. It is just required that the GW background not contribute a signal which is detectable in the timing residuals of one or more pulsars. A 7-yr span of 1400-MHz Arecibo observations of PSR B1855+09 which showed no evidence for low-frequency timing noise was used to place a limit on Ω_{gw} , the ratio of the energy density of the GW background in the Galaxy to the closure density of the Universe, of about 10^{-7} [32, 33]. By combining this data set with PPTA observations of seven pulsars Jenet et al. [34] were able to reduce this limit by about an order of magnitude, constraining some models of the relic GW background and cosmic strings. This result and its implications are discussed in more detail by Hobbs et al. in these Proceedings.

A PULSAR TIMESCALE

International Atomic Time (TAI) is defined by a weighted average of many atomic clocks (mostly caesium standards) located at time and frequency laboratories around the world [35]. The most precise terrestrial timescales available are retroactive revisions to TAI published by the BIPM [36], the latest of which is TT(BIPM06).² They differ from TAI by up to several microseconds and from each other by several tens of nanoseconds, corresponding to apparent stabilities $\sigma_y \sim 10^{-15}$ [35].

A timescale based on pulsars differs fundamentally from these atomic timescales. First it is based on entirely different physics — rotation of massive bodies — and is largely isolated from Solar-system and Earth-based effects. Furthermore, pulsars will continue spinning for billions of years, whereas man-made clocks have a lifetime measured in years or decades at best. Since cur-

rent ToA precisions are at best tens of nanoseconds, stabilities comparable to those of atomic clocks can only be reached over intervals of several years. The pulsar timescale is not absolute as it is based on *a priori* unknown pulsar periods, so the accuracy of the atomic timescales cannot be checked, only their stability. Fig. 5 shows the stability parameter σ_z [37] for two pulsars with long data spans together with the same statistic for the difference between two of the most stable atomic timescales, the German-based UTC(PTB) and the US-based UTC(NIST). It is clear that, for averaging times of several years or more, the period stability of MSPs is comparable to and maybe exceeds that of the best available atomic clocks. Pulsar timing arrays promise even greater stability as fluctuations in individual pulsars can be averaged over [38]. We can envisage use of a weighted averaging scheme similar to that applied to the atomic time standards. Such a pulsar timescale should give better than 50 ns precision at intervals of weeks and 5 ns precision for fluctuations with timescales of years, corresponding to a stability of 10^{-16} or better.

THE FUTURE

The sensitivity of a pulsar timing array to a stochastic GW background is proportional to the average ToA precision, the square root of the number of observations (ToAs) and, in the conservative case of no prewhitening, to the number of pulsars in the array [29]. The simulations show that the PPTA alone can just detect the GW background if it reaches its sensitivity goals. Clearly it is desirable to increase the number of pulsars observed, the frequency of observation and the precision of each observation. As discussed above, we are working on the precision aspect, but it is difficult to significantly increase the number of pulsars and frequency of observation for the PPTA. Furthermore, the PPTA is of course limited to pulsars at declinations south of $+25^\circ$, the northern limit of the Parkes telescope. A wider distribution on the sky would help in the separation of the different sources of period fluctuation. It would also be especially valuable for detections of individual sources of GW, helping to localise them on the sky.

All of these factors point toward the desirability of establishing international collaborations with other pulsar timing array projects. We have already established a collaboration with the European Pulsar Timing Array (EPTA) project [39], with agreement on data sharing, coordination of observing schedules and collaboration on data analysis and interpretation. Future collaborations with the North American and Chinese pulsar timing groups, perhaps forming a “World Pulsar Timing Array”, are under active discussion.

² The TT(BIPMxy) timescales may be obtained from the Time, Frequency and Gravimetry FTP server at <http://www.bipm.org>.

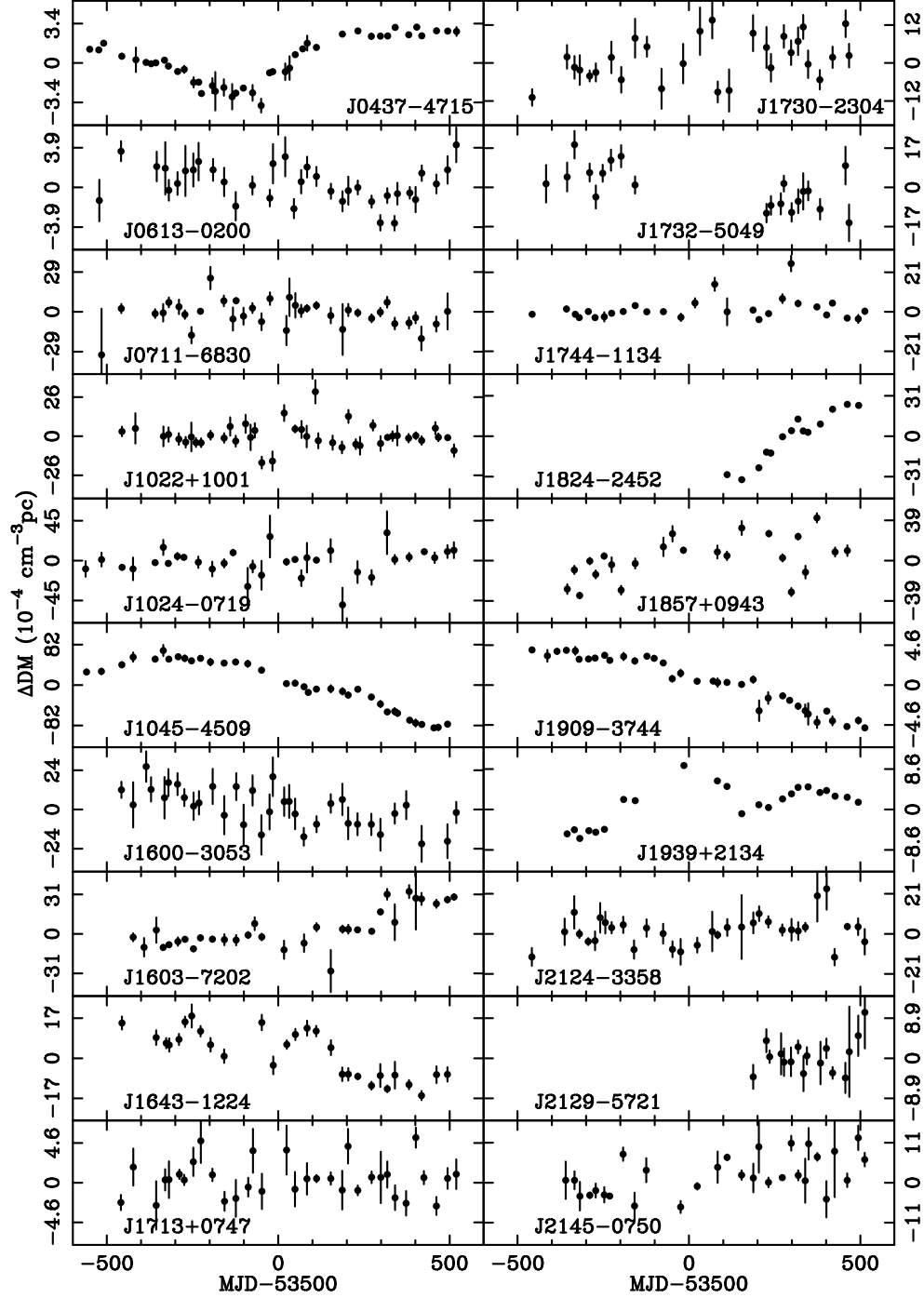


FIGURE 4. Observed variations in dispersion measure for the PPTA pulsars obtained by comparing contemporaneous 10cm/50cm or 20cm/50cm ToAs [31]

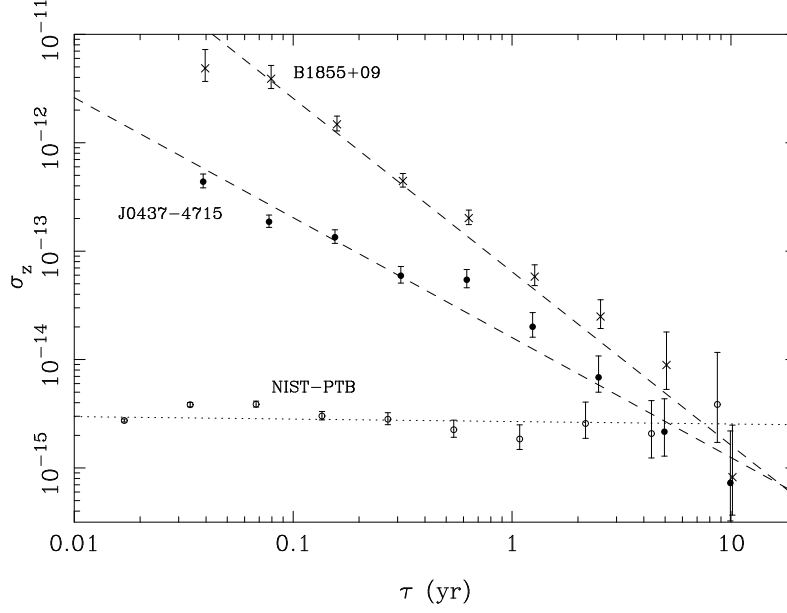


FIGURE 5. Clock stability parameter σ_z against averaging time for two pulsars, PSR J0437–4715 and PSR B1855+09, and for the difference between UTC(PTB) and UTC(NIST).

Looking further to the future, the proposed Square Kilometer Array (SKA) will have a huge impact on pulsar timing projects. With its enormous sensitivity and ability to multi-beam, sharing telescope resources with other projects, sensitive searches and frequent high-sensitivity observations a large sample of pulsars should be possible. As an example, let us assume weekly observations of a sample of 100 MSPs at two or three frequencies with ToA precisions of order 50 ns. Let us further assume that such observations continue for 10 years and take the conservative case of no prewhitening. Provided intrinsic timing noise in the pulsars does not dominate the effect of the stochastic GW background, this corresponds to a detection limit at 3 nHz of $\Omega_{\text{gw}} \sim 2 \times 10^{-13}$. Pre-whitening has the potential to decrease these limits, but the ultimate level reached will depend strongly on whether or not MSPs exhibit significant intrinsic timing noise at these levels of precision over these long data spans.

Fig. 6 shows the sensitivity of existing and proposed GW detectors, illustrating the complementary nature of the different classes of detector. Expected signal levels from relevant astrophysical sources in the different frequency bands are also shown. These cover a range of strain levels. In some cases, for example, neutron star – neutron star coalescence, this range reflects the statistical uncertainty in the occurrence rate of detectable events, whereas for the sources at nHz frequencies to which the pulsar timing arrays are sensitive, it more reflects the uncertainty in the theoretical models on which the predictions are based. For example, Grishchuk [2] predicts a

much higher level of relic GW from the inflationary era than the standard models of inflation [1, 40]. Sensitivity curves are given for the current pulsar limits [34], the sensitivity goal of the PPTA project and the 10-year SKA timing array project as described above. With a 15-year data span, the predicted detection limit is approaching the background level expected from standard inflation. Current observations are beginning to limit other inflation models and models for generation of GW by cosmic strings, but do not yet significantly limit models for formation and evolution of super-massive binary black holes in the cores of galaxies. The design goal for the PPTA would either detect this stochastic background or essentially rule out all current models for its formation. The SKA would give detections with high significance enabling detailed studies of the source and signal properties — an exciting prospect!

CONCLUSIONS

Pulsar timing arrays exploit the remarkable stability of MSP periods to enable investigation of a range of phenomena. Direct detection of gravitational waves from astrophysical sources is a major goal of current astrophysics and pulsar timing arrays have the potential to achieve this goal. They are sensitive to GW at frequencies of a few nanoHertz, complementing ground-based and space-based laser interferometer systems which are sensitive at much higher frequencies. PTA systems also have the potential to establish a “pulsar timescale” which

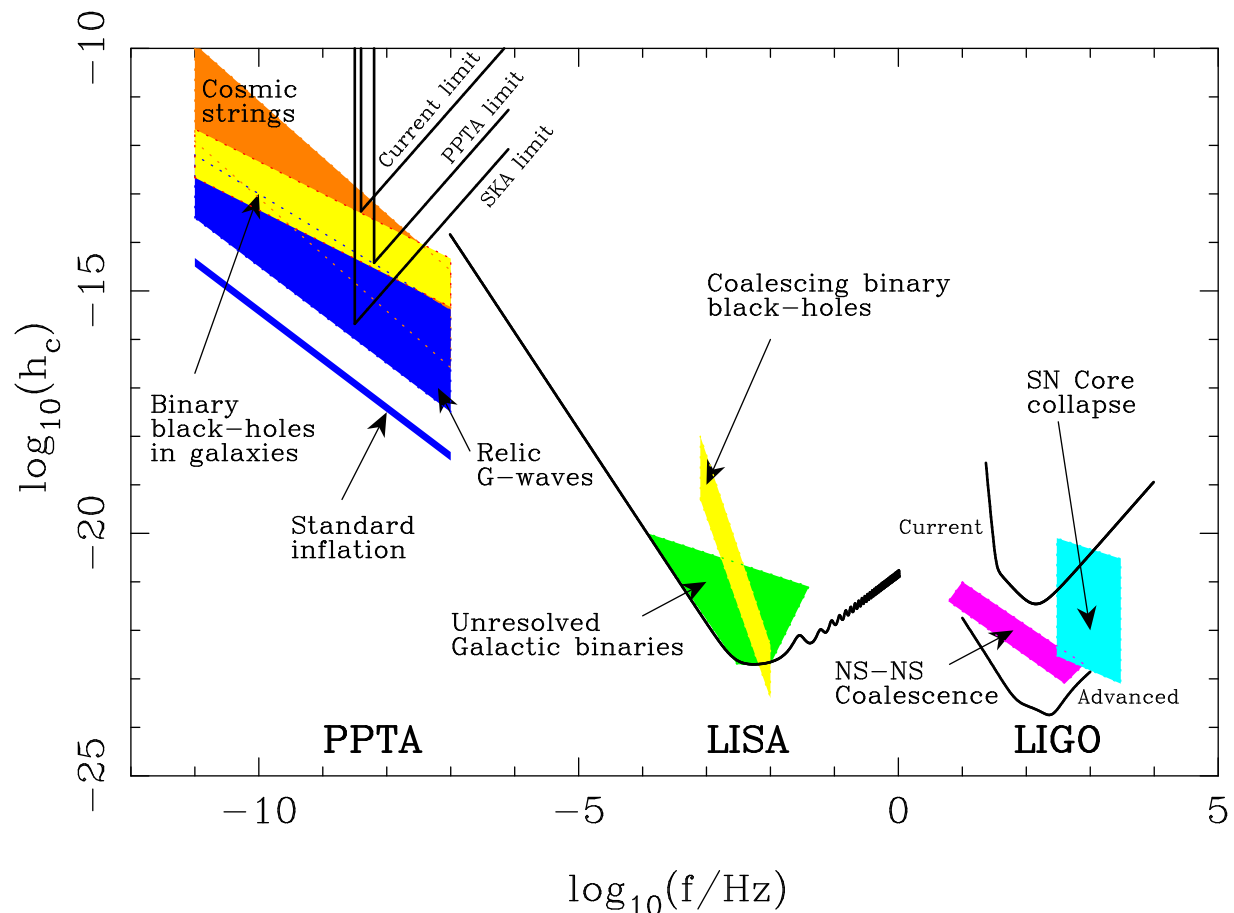


FIGURE 6. Characteristic strain sensitivity for existing and proposed GW detectors as a function of GW frequency along with the expected levels for signals from some relevant astrophysical sources.

is more stable than the best terrestrial timescales over intervals of several years or more and to detect errors or omissions in models of Solar-system dynamics, for example, the existence of currently unknown trans-Neptunian objects.

The Parkes Pulsar Timing Array (PPTA) project is using the Parkes 64-m radio telescope to time a sample of 20 millisecond pulsars at three frequencies every 2 – 3 weeks. Observations commenced in early 2005, so we now have over two years of timing data. Sub-microsecond timing residuals have been achieved on about half the sample but we still need to improve timing precisions by a factor of a few in order to have a realistic chance of detecting the stochastic GW background. New instrumentation and other improvements will help us to achieve that goal. We are also actively seeking international collaborations with other timing array projects to increase the sky coverage and the density of observations. Already, limits on the GW background are starting to limit some inflation-era and cosmic string models. There seems little doubt that the proposed Square

Kilometer Array radio telescope will be able to not only detect GW but to also study the properties of the GW sources in some detail, opening up a new era in astrophysics.

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